MIT Space Engineering Research Center

INTELLIGENT STRUCTURES TECHNOLOGY

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Controlled Structures Technology
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Overview

- Embedding electronic components for control of intelligent structures.
- Single-chip microcomputer control experiment
- Structural shape determination
- Distributed sensor systems for structural control

Motivation

- Precision control of flexible structures is more readily achieved with large numbers of sensors and actuators
- Signal quality can be improved by distribution of analog processing circuitry along with transducers
- Connectivity (number of lines) can be greatly reduced by distribution of A/D, D/A conversion with digital bus interface circuitry
- Control loop speed can be substantially elevated by distribution of digital processors in a hierarchic controller

Missing element in fully integrated intelligent structures concept:

embedded electronics

Objectives

Establish the feasibility of physically embedding electronic components for the control of intelligent structures.

Demonstrate structural control using processor with minimal number of chips

Embedding Electronics: Approach

- Select a suitable candidate chip for embedding
- Develop embedding technique
- Test mechanical static and fatigue properties
- Test temperature-humidity-bias reliability

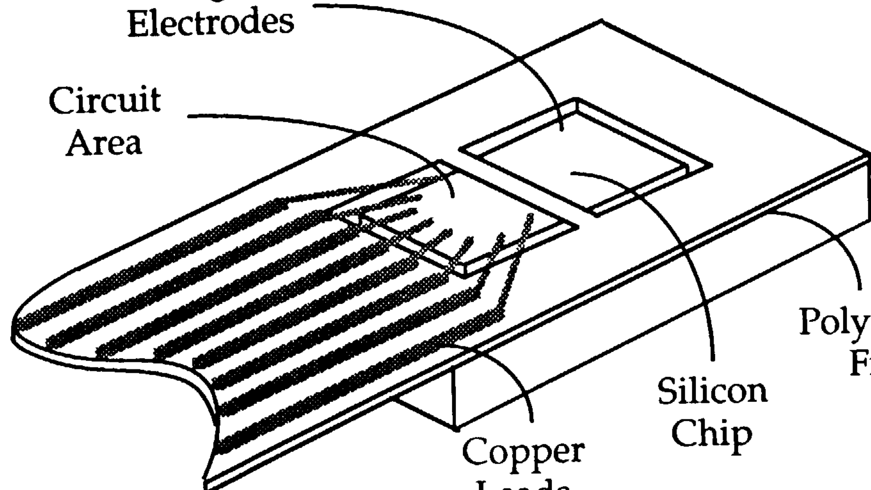
Electrical and Mechanical Compatibility

Issues:

- Manufacturing - autoclave pressures and temperatures
- Operational mechanical stress – brittle Si, delicate SiO_2 and metal structures
- Electrical insulation from graphite fibers
- Ionic contamination – device lifetime is typically limited by corrosion
- Minimal disruption of structural plies

Integrated Circuit Chip Packaged for Embedding

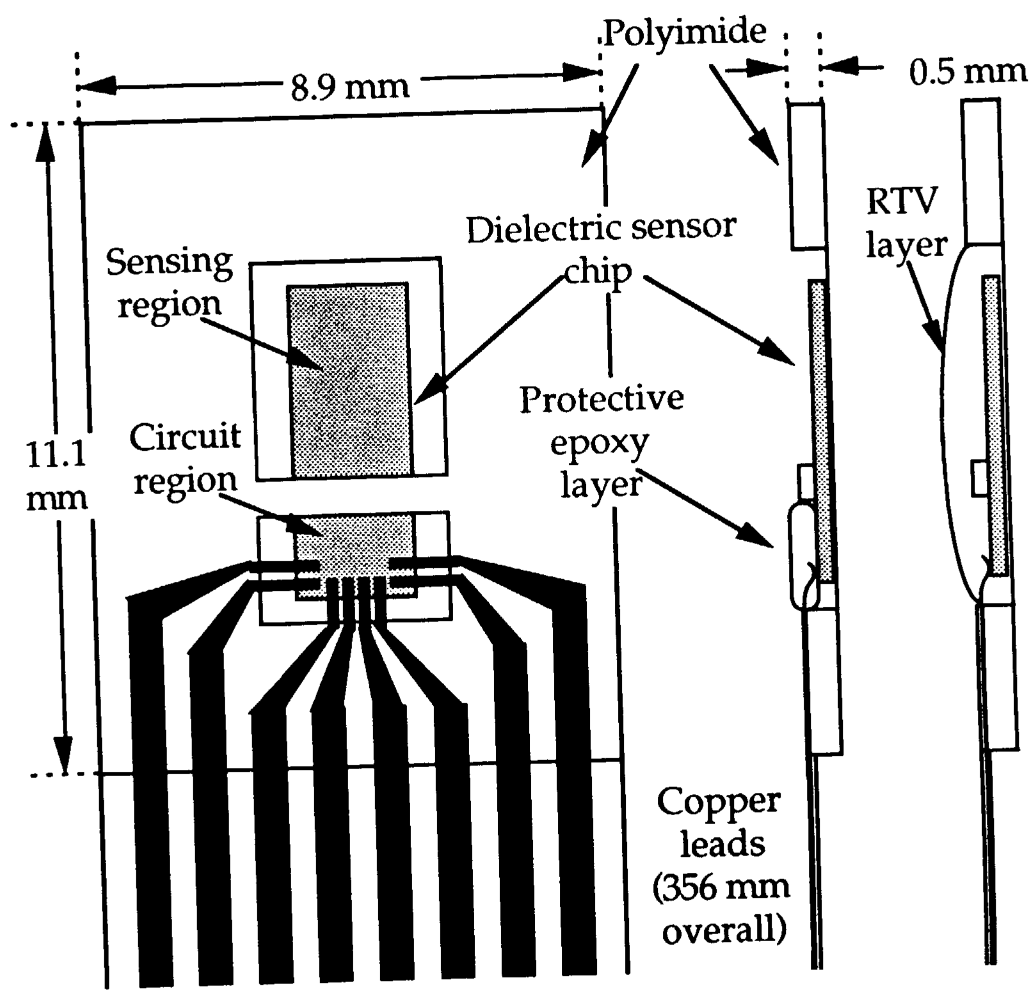
Dielectric integrated circuit sensor (Micromet Instruments, Inc.)



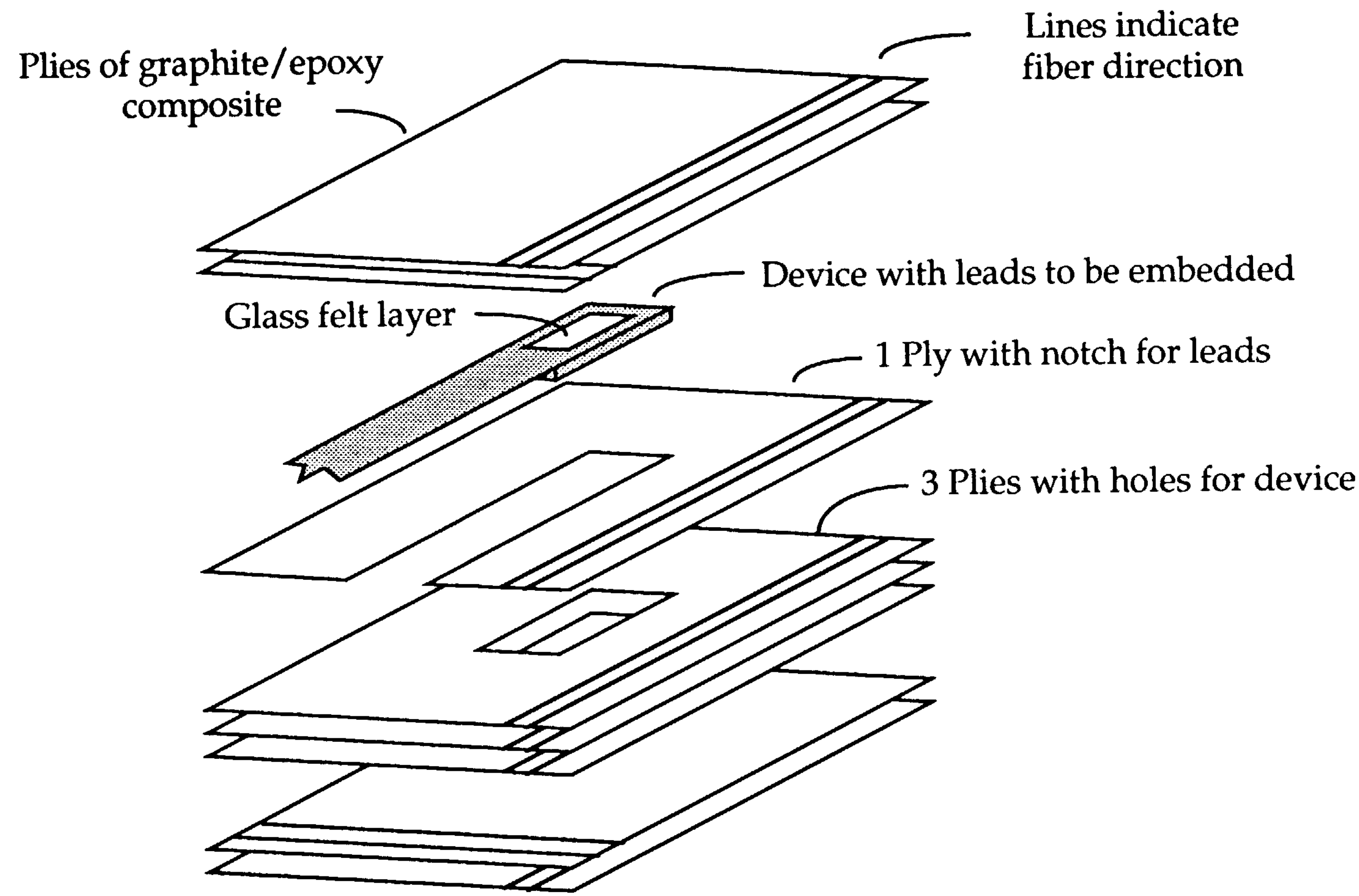
Circuit area consists of two metal-oxide-semiconductor field effect transistors and one diode

Packaging is similar to Tape Automated Bonding (TAB)

Integrated Circuit Chip Packaged for Embedding

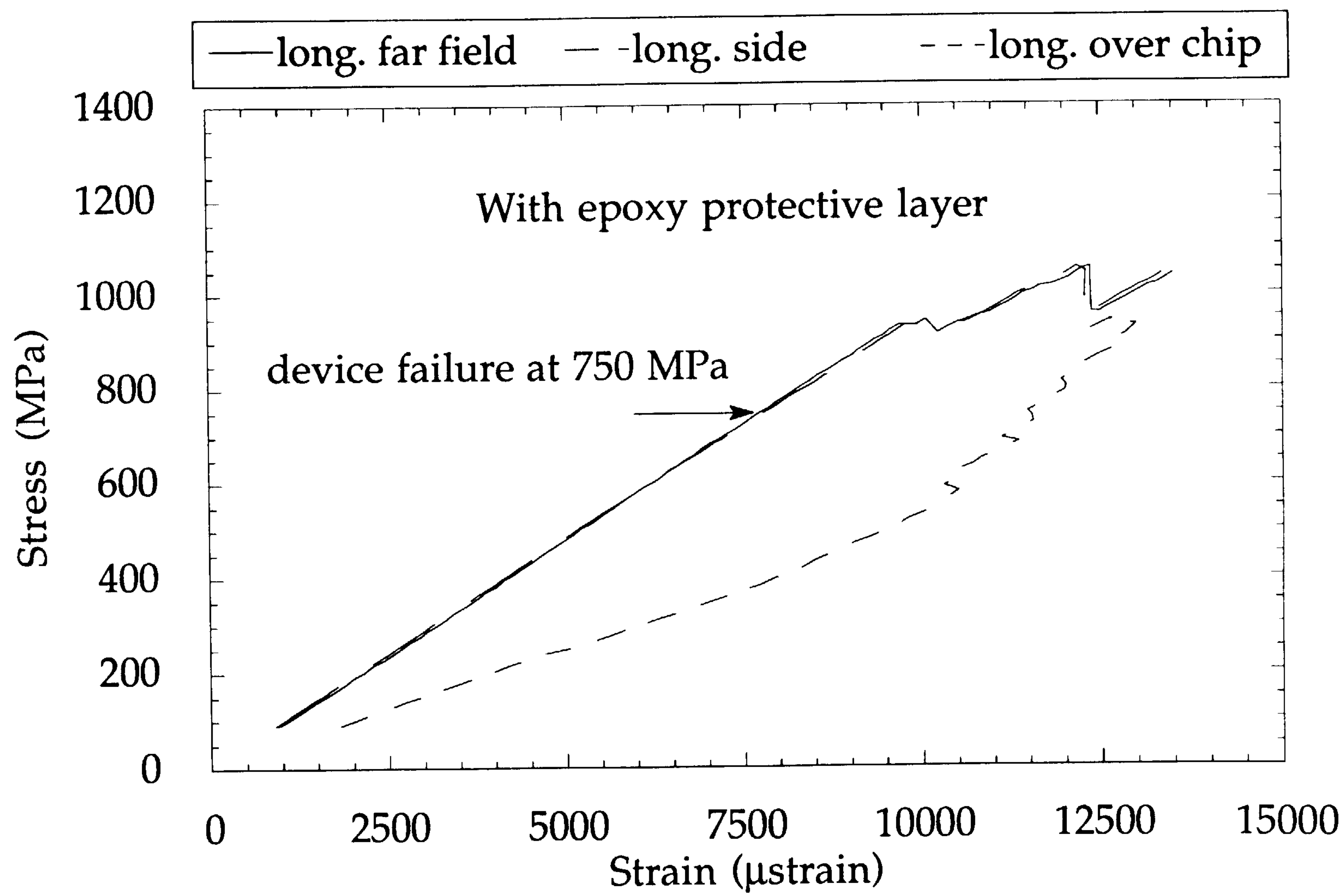


Embedding Devices within Composite Structures

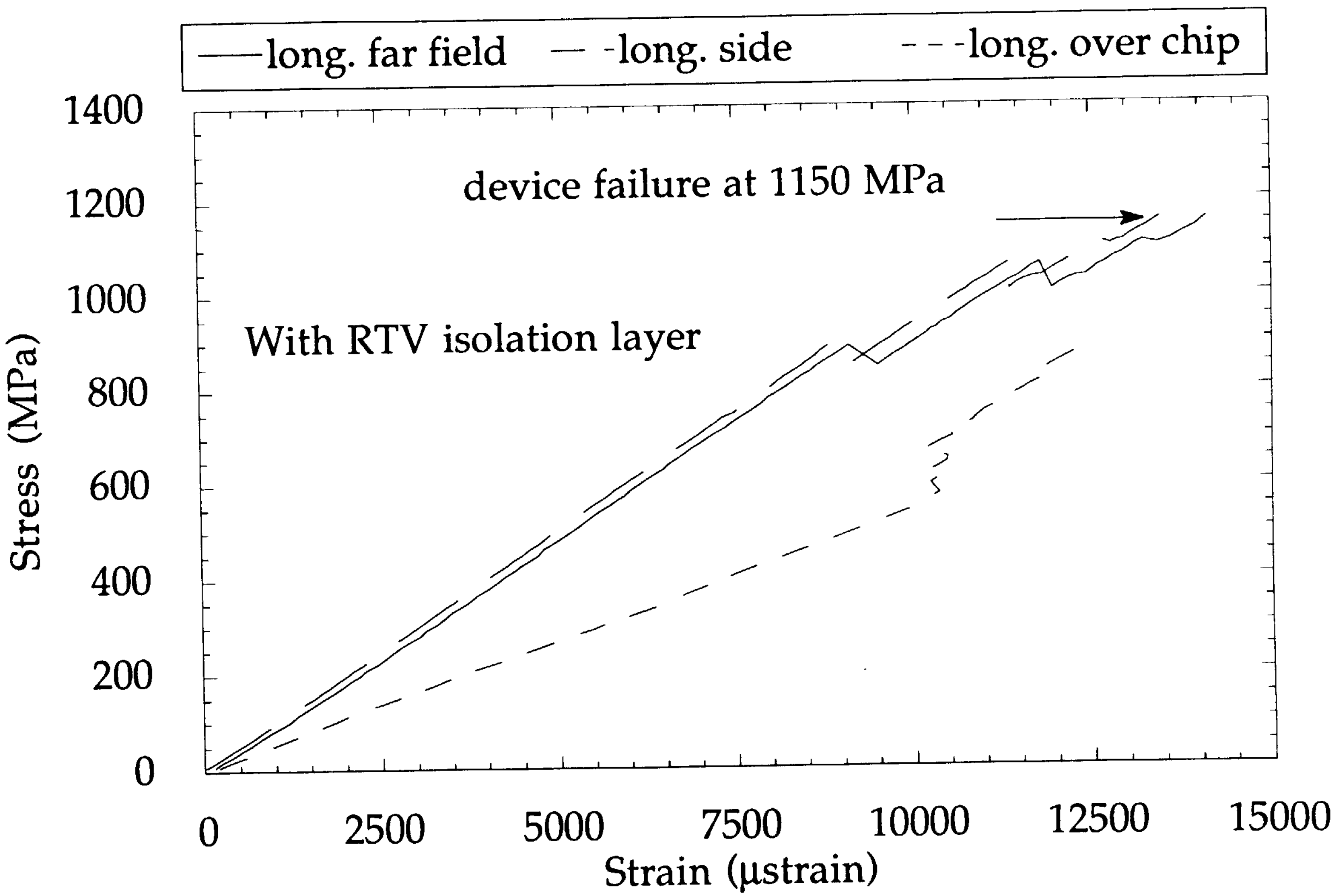


Layup is $[0/90/0_2]_S$

Test of Embedded Circuit in G/E Coupon



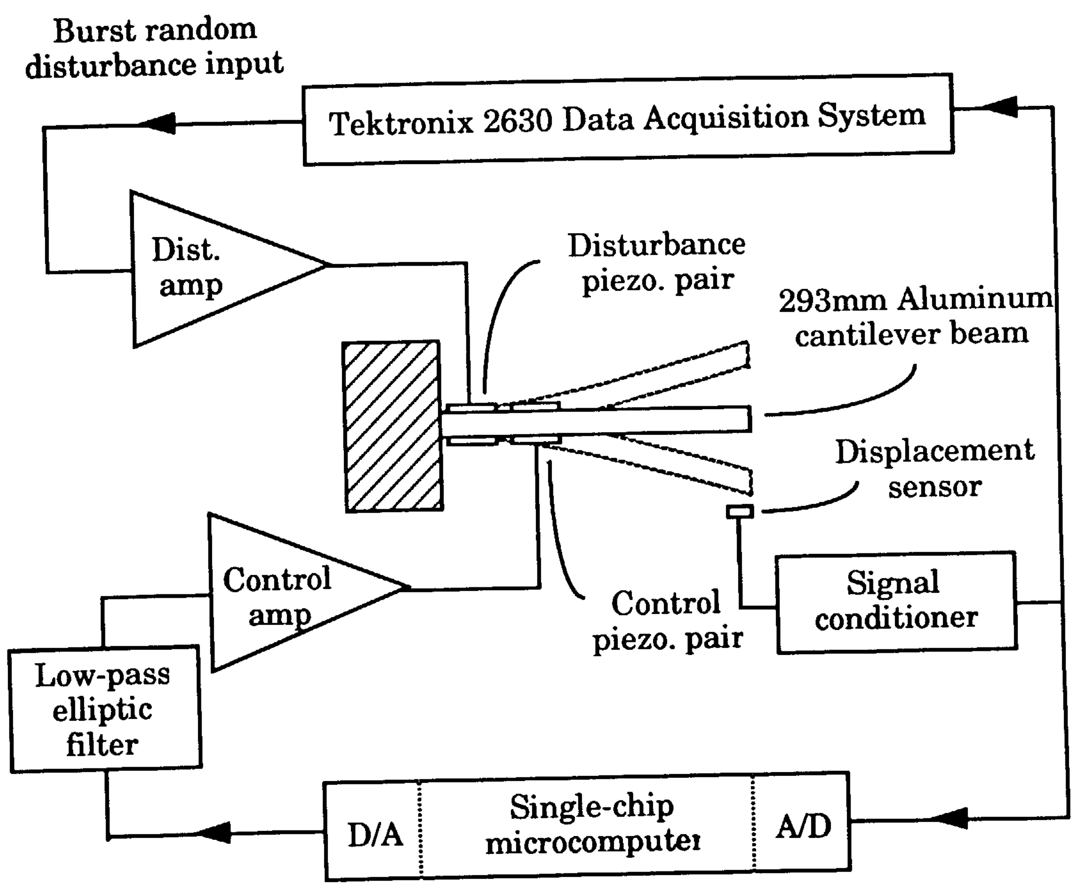
Test of Embedded Circuit in G/E Coupon



Temperature/Humidity/Bias Test

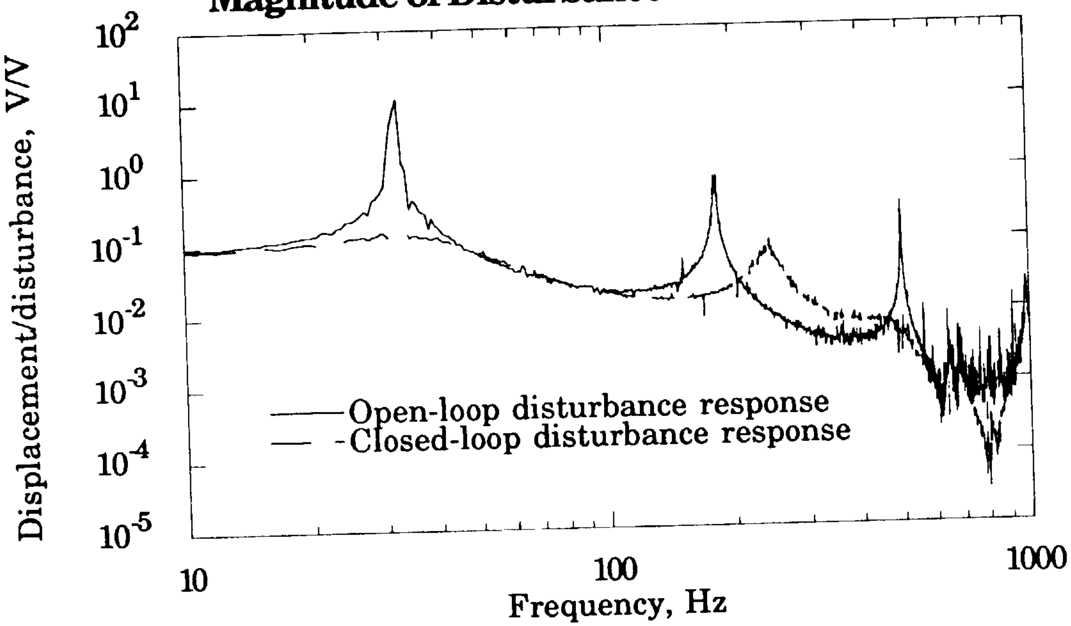
- Test conditions:
  - 3 chips embedded in 60 mm x 75 mm laminates subjected to 80°C and 80% R. H. for 125 hours
  - Transistor drain-source currents while under constant bias continuously monitored; characteristic curves recorded at log time intervals
  - Two conventional MOSFETs included as experimental controls
- Results:
  - One sensor showed intermittant anomalies (hysteresis, elevated current) as early as 14 hours - possible leakage currents through epoxy
  - One sensor showed progressive drop in current during final 4 hours - consistent with lead corrosion
  - One sensor showed no anomalies
  - Conventional controls showed no anomalies

Single-chip Microcomputer Control Experiment



Performance Achieved

Magnitude of Disturbance Transfer Function



Increased damping:	1st mode	0.36% OL	31% CL
	2nd mode	0.15% OL	4% CL
	3rd mode	0.20% OL	11% CL

Major Results

- Embedding electronics is feasible

  Compliant isolation layer allows device function to laminate failure

  Chemical isolation is inferior to commercial devices, requires further work

  All failures were at or near lead-chip bond

- Embedding local processors are plausible

  Distribution of processing can be justified, depending on problem size

  Nearly all of the required functions included on currently available monolithic devices

Structural Shape Determination Objectives

Objective is to determine "optimal" type and number of sensors to allow accurate reconstruction of structural shape from discrete curvature measurements.

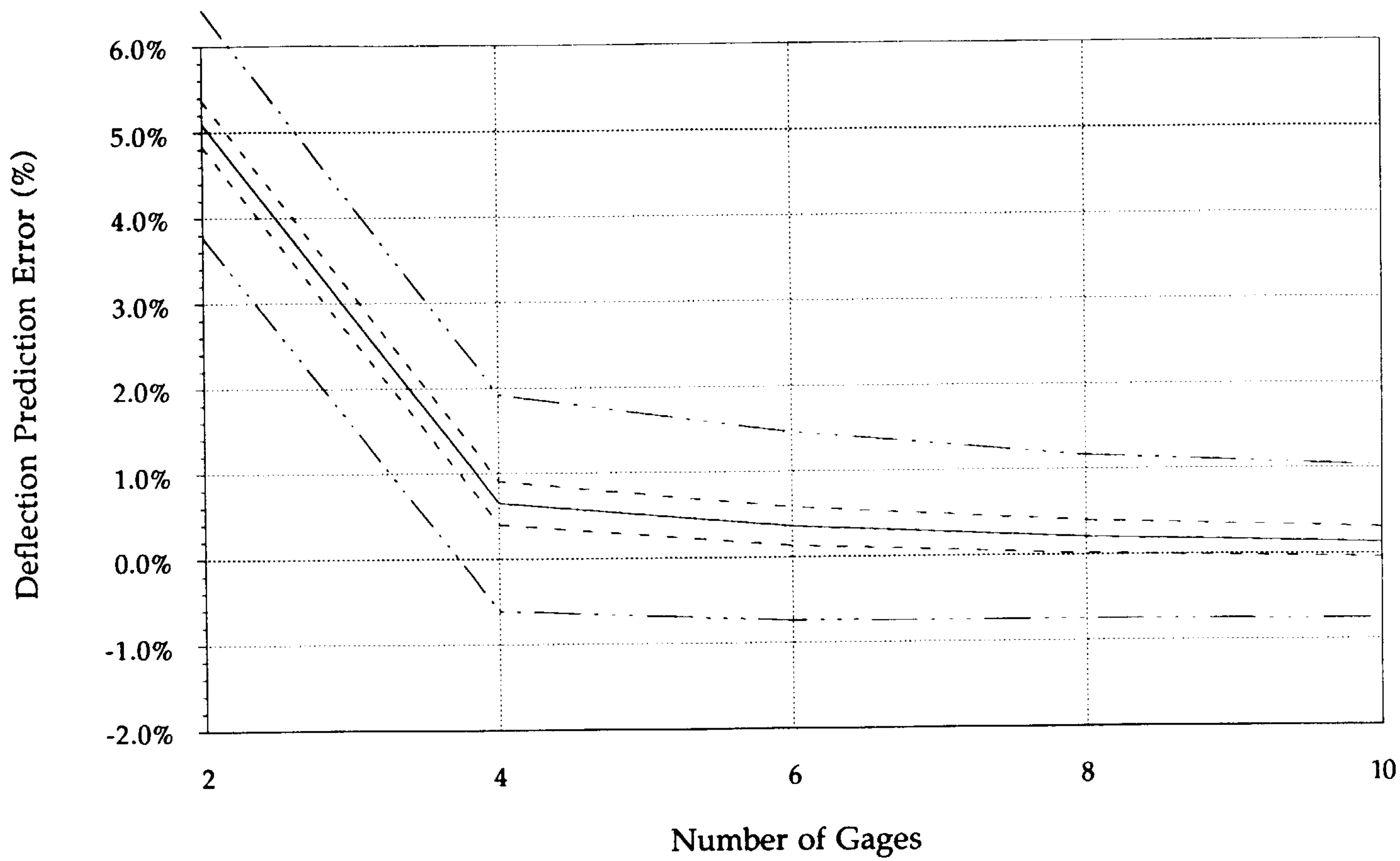
Issues considered include:

- Accuracy of predicted slope and displacement for various integration rules as a function of the number of gages.
- Static and dynamic mode shape determination with strain averaging sensors.
- Frequency characteristics of a single sensor.
- Frequency characteristics of integrated shape measurement.

Approach to Integration Rule Study

- Consider a cantilevered beam subjected to a representative set of simple static loadings.
- Distribute a set of strain gages along the length of the beam/
- Integrate the curvature using a variety of integration rules to obtain an estimate of the shape of the beam.
- Vary gage factor and gage placement to obtain error bounds for experimental uncertainties.
- Compare performance of short and long gages to determine whether a "point" or an averaged strain measurement yields better performance.

Deflection Prediction Error vs Number of Gages



Spline integration rule and long gages

Solid line:	No gage factor or placement error.
Dashed line:	1% gage factor error and placement error of 0.2% of the beam length.
Dot-dashed line:	5% gage factor error and placement error of 1% of the beam length.

Functional Requirements for Distributed Sensor Systems

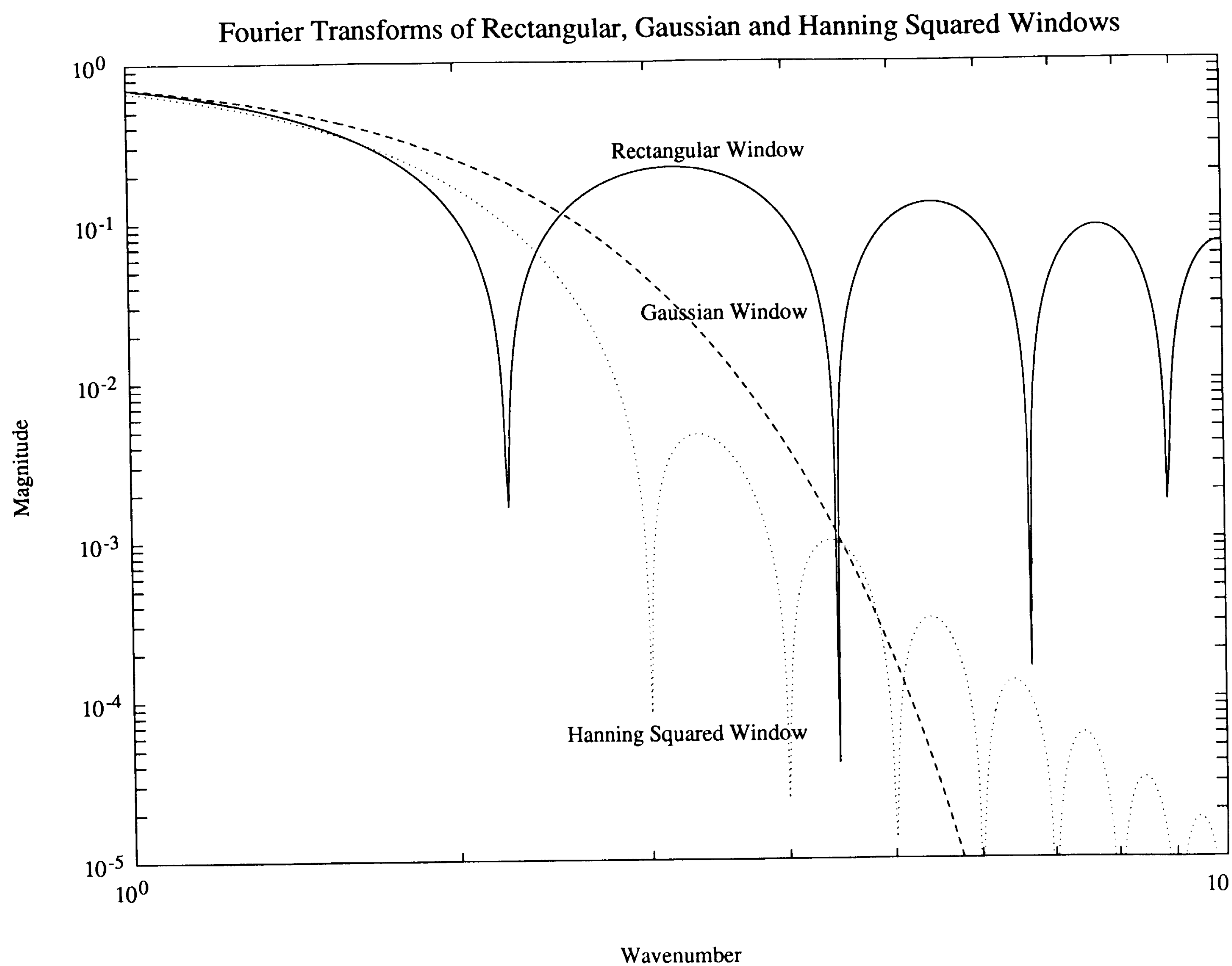
- The sensors should be able to sense static modes and resolve them in detail.
- The integral of the static shape, and therefore output of each sensor should roll off quickly in frequency and not have negatives.
- The sensors must have good observability of the dynamic modes targeted for control in the bandwidth.
- The observability of dynamic modes must roll off quickly beyond the control bandwidth.
- The sensors should be easily implementable and must be finite in length.
- If possible, the sensors should not contain negative regions.

Approach

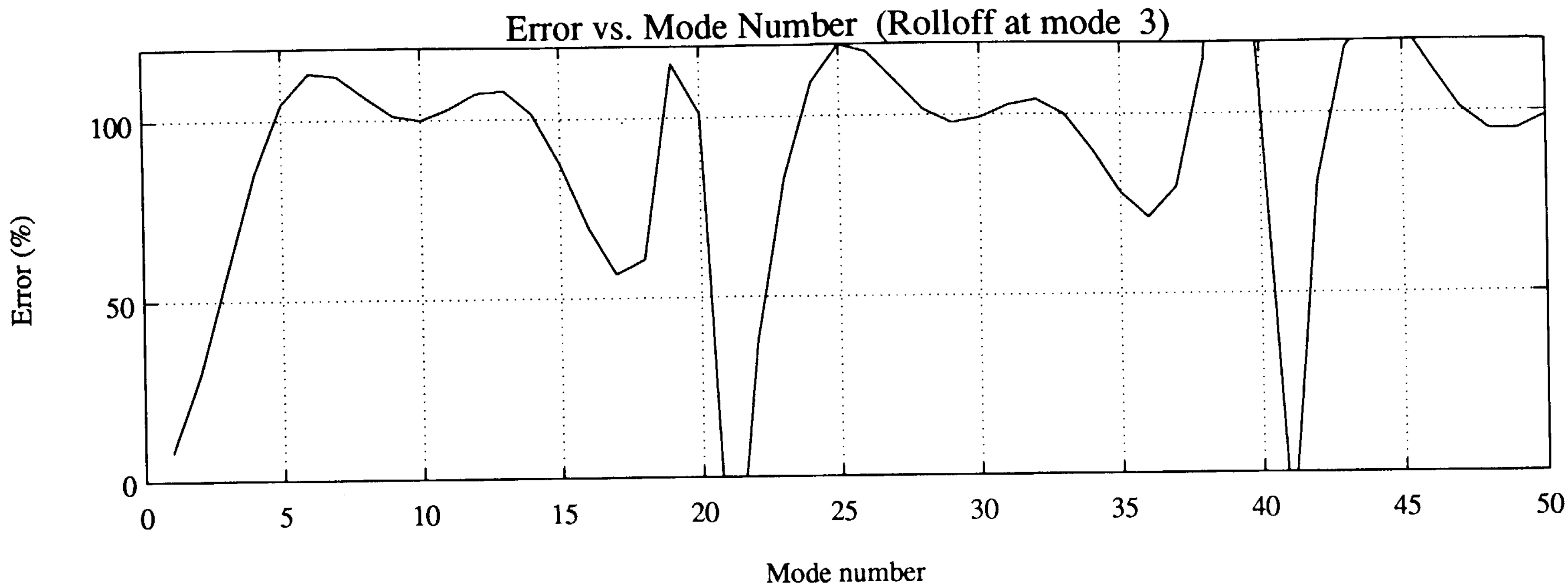
- Consider a pinned-pinned beam with 9 gages distributed along its length.
- Vary the length and spatial weighting of the gages.
- Integrate the sensor measurements to obtain an estimate of the shape of the beam.
- Increase the frequency of the dynamic mode of the beam, and examine the behavior of the tip deflection estimate.
- Verify that observability rolls quickly and monotonically approaches zero.
- Optimize the roll off characteristics by varying spatial weighting of the sensors.

Examples of Single Sensor Characteristics

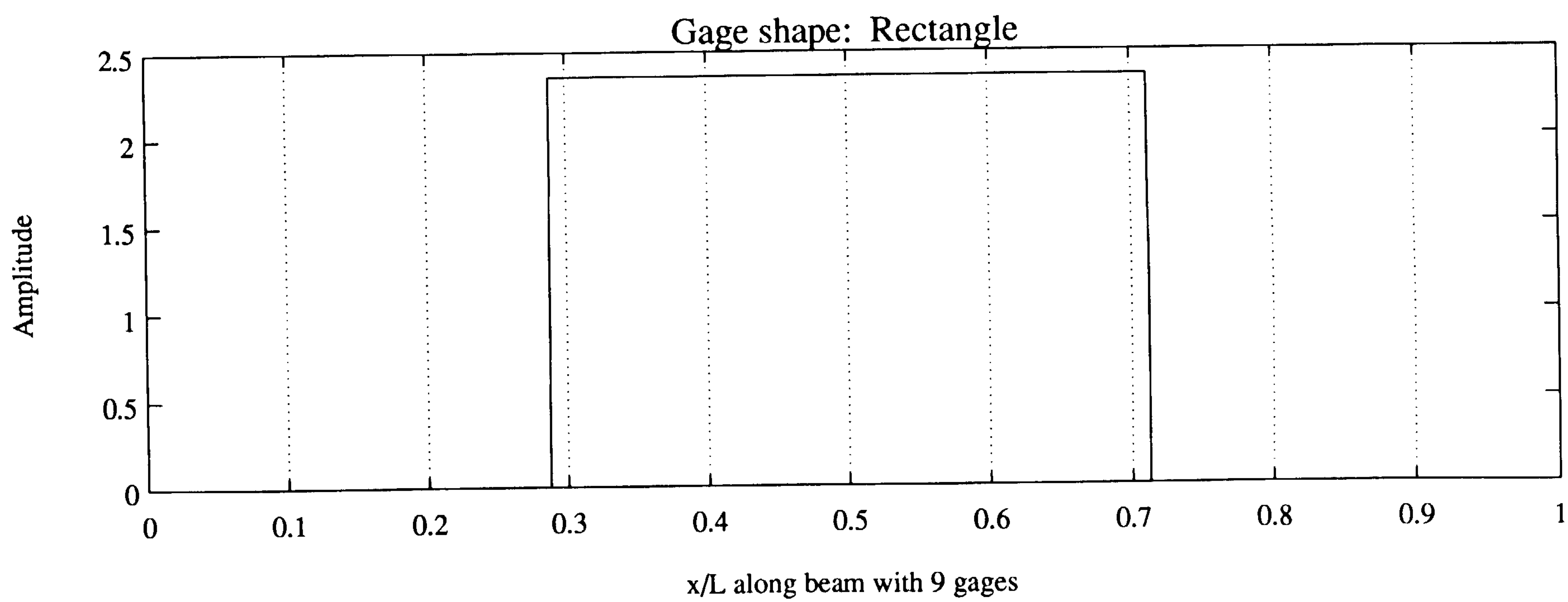
Shape	Advantages	Disadvantages
Sinc	Gives perfect rolloff with no phase lag.	Is of infinite extent in x. Has negative regions in x. Hard to manufacture and distribute.
Rectangle	Very simple shape. Can be distributed easily. Has no negative regions in x.	Only -20 db/decade rolloff. Has large negative regions in k.
Gauss	Has no negative regions in x or k. Has good rolloff (-300 db in 1st decade). Can be distributed.	Is of infinite extent in x.
Hanning^2	Has no negative regions in x. Has good rolloff (-100 db/decade) Can be distributed.	Has small negative regions in k.



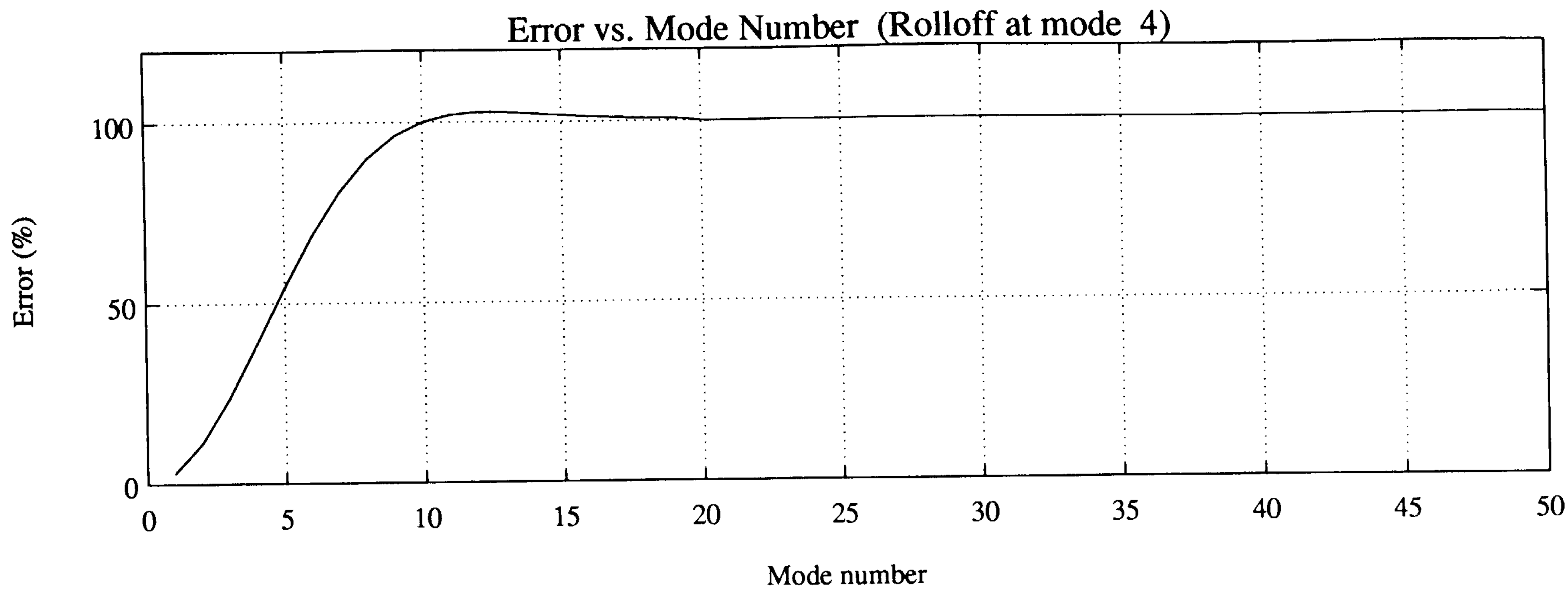
Fourier Transforms of Rectangular, Gaussian and Hanning Squared Windows
Rectangular Window
Gaussian Window
Hanning Squared Window
Magnitude
Wavenumber
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^0
10^1



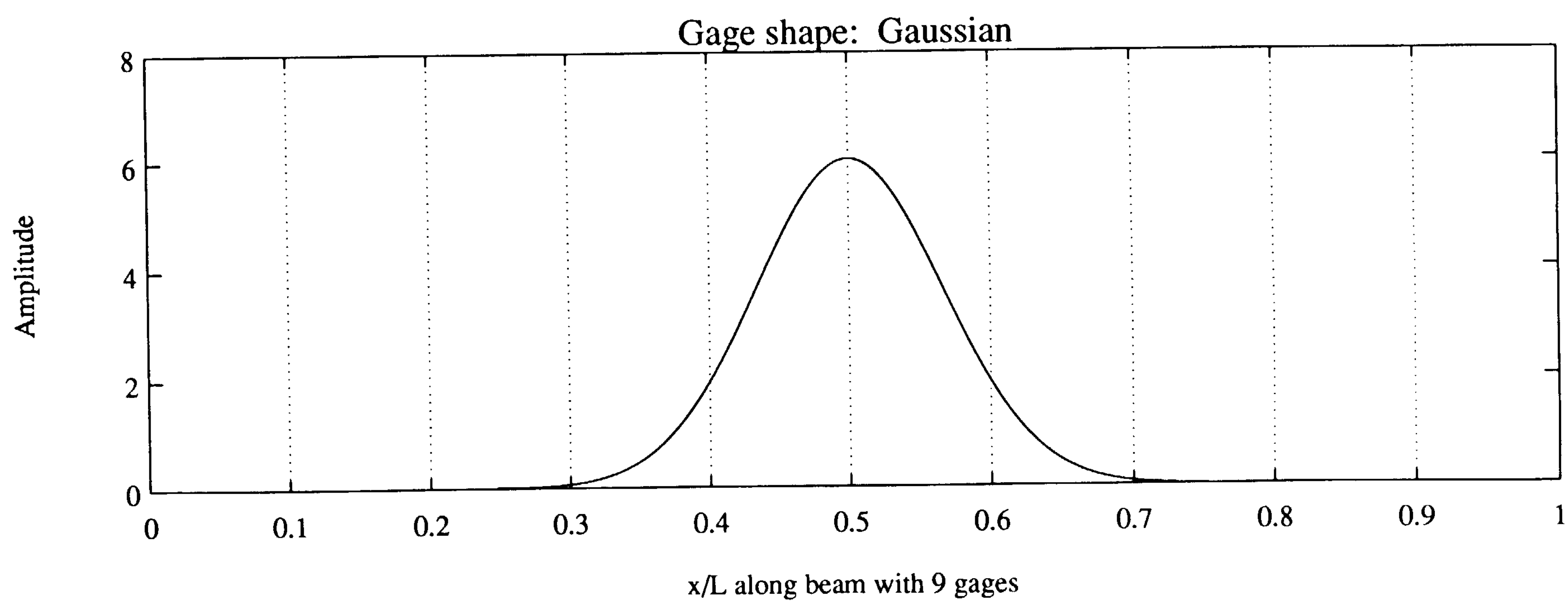
Error vs. Mode Number (Rolloff at mode 3)
Error (%)
100
50
0
0
5
10
15
20
25
30
35
40
45
50
Mode number



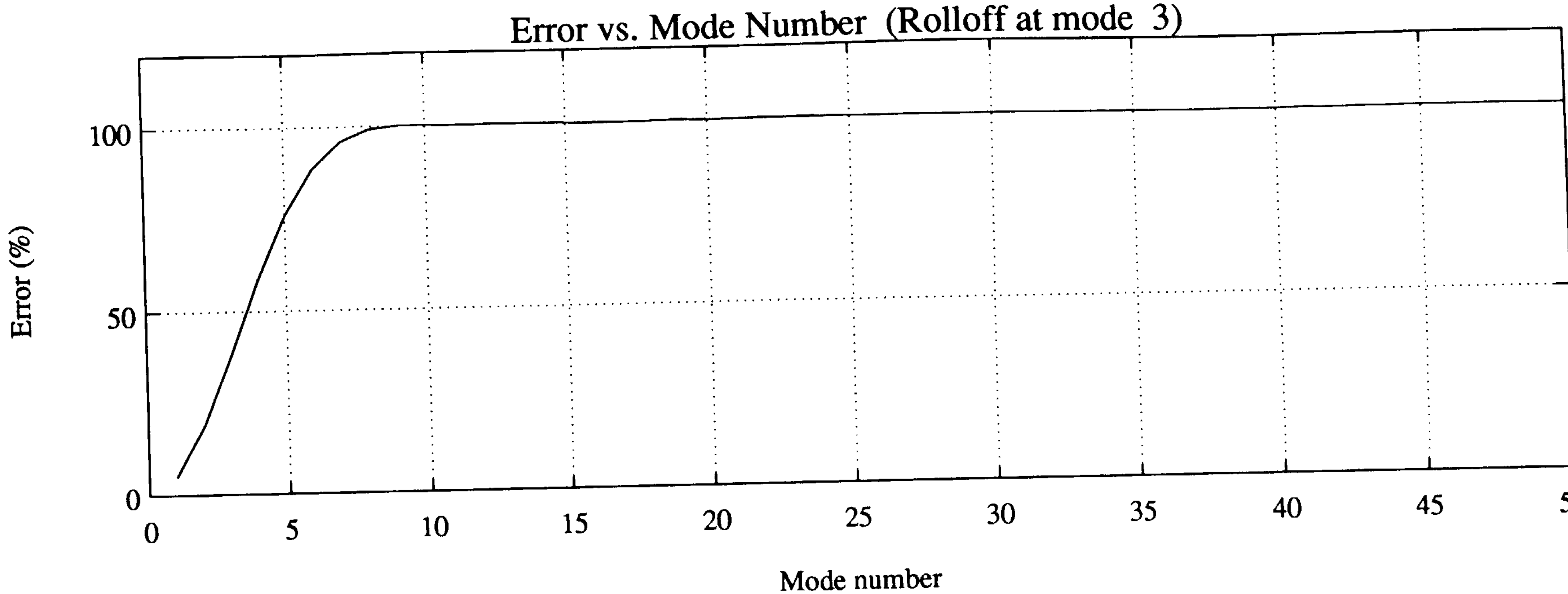
Gage shape: Rectangle
Amplitude
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/L along beam with 9 gages

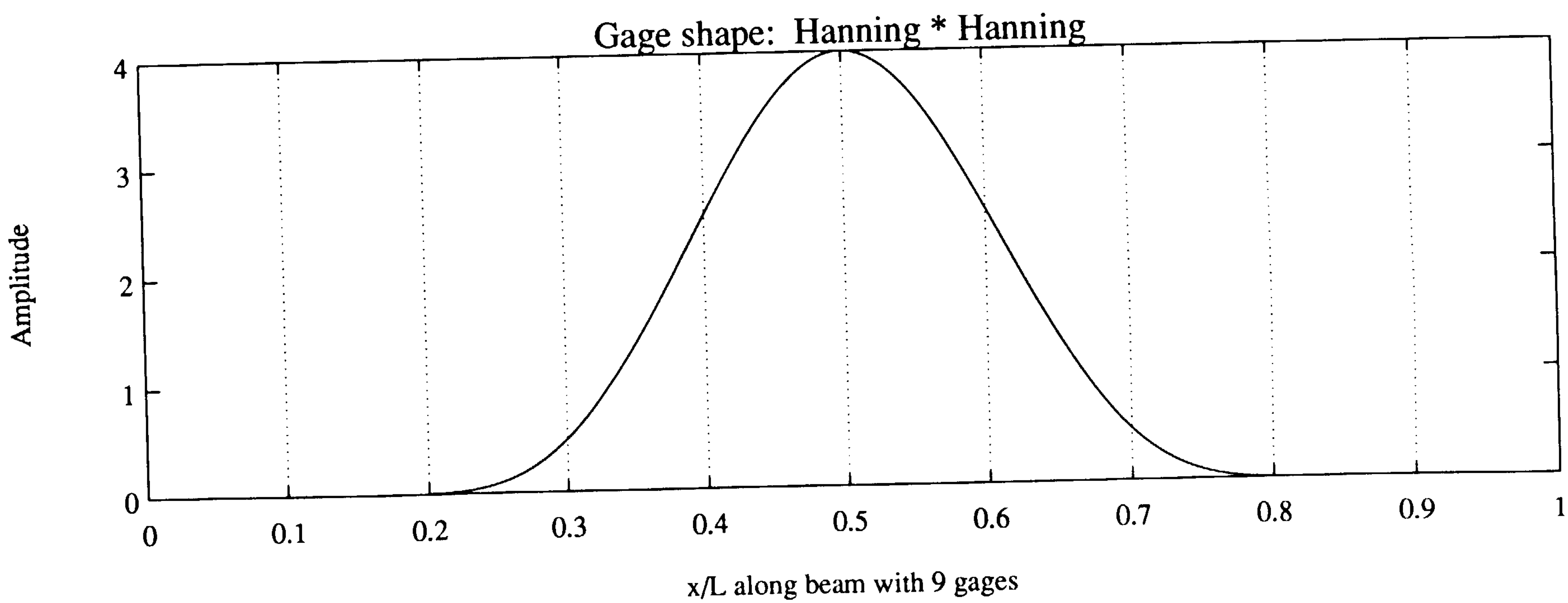


Error vs. Mode Number (Rolloff at mode 4)
Error (%)
100
50
0
0
5
10
15
20
25
30
35
40
45
50
Mode number



Gage shape: Gaussian
Amplitude
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/L along beam with 9 gages


Error vs. Mode Number (Rolloff at mode 3)
Error (%)
100
50
0
0
5
10
15
20
25
30
35
40
45
50
Mode number


Gage shape: Hanning * Hanning
Amplitude
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/L along beam with 9 gages

Conclusions

- Numerical integration schemes have been found that yield accurate shape prediction with a minimum of sensors.
- Spatial weightings for distributed sensors have been identified that yield quick rolloff in:
  - Individual outputs of each sensor
  - Integrated output of all the sensors (tip displacement)
- The functional requirements can nearly be met by simple sensor shapes that are relatively easy to implement.
- Meaningful experiments must be carried out in order to verify theoretical predictions and determine sensitivity of performance to errors incurred during physical implementation of a distributed sensor system.